The Run II Physics Program

John Womersley

Fermi National Accelerator Laboratory, Batavia, Illinois

Representing the CDF and DØ collaborations

Not the "Run IIb" physics program …

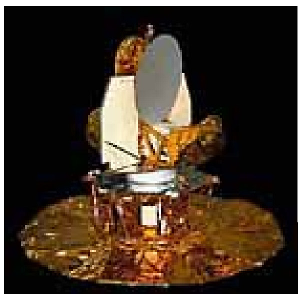
- There is a single Tevatron physics program which evolves as a function of luminosity
  - There is interesting physics at all luminosities, starting now with 50-100 pb^{-1} and continuing through 0.3, 1, 2, 5, 10, 15 fb^{-1}

- This physics program has begun

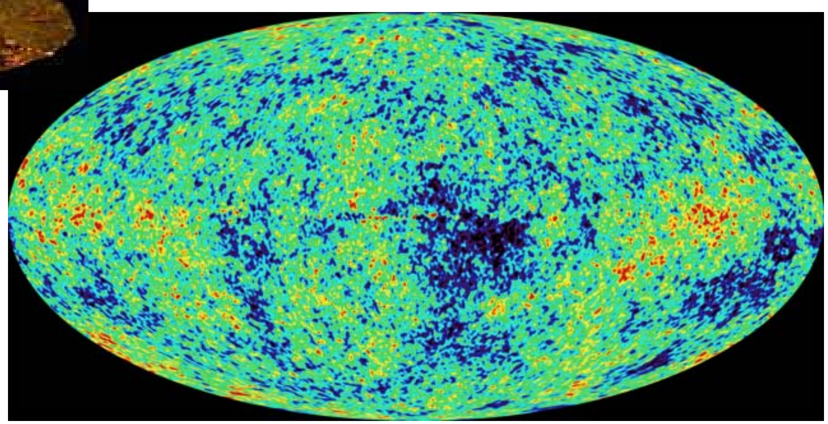
- The goal of the Run IIb detector upgrades is to
  - maximize this physics program
  - exploit the full potential of the world's highest energy collider and the large investments we have made in the accelerator and detectors
  - Lay a firm foundation for the LHC and for future initiatives at the TeV scale

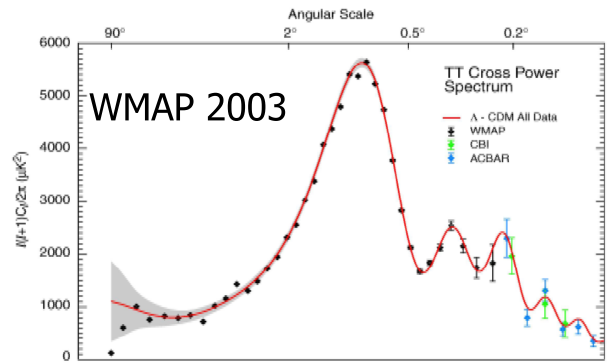
Big Questions at the Electroweak Scale

- **The Tevatron is the only accelerator in operation that can help to answer**
  - **What is the structure and what are the symmetries of space-time?**
  - **Why is the weak force weak?**
  - **What is cosmic dark matter made of?**



About six to seven times more mass in the universe (27±4%) than there is baryonic matter (4.4±0.4%)





What is this stuff? How can we get a firmer understanding of it?

Accelerators

- **Run II is the only opportunity to make such a major discovery in the USA**

John Womersley

The program

- **The Run II Physics program**
  - **Confronts the standard model through precise measurements**
    - **the strong interaction, the quark mixing matrix, the electroweak force and the top quark**
  - **Directly searches for particles and forces not yet known,**
    - **Those predicted and those that would come as a surprise**

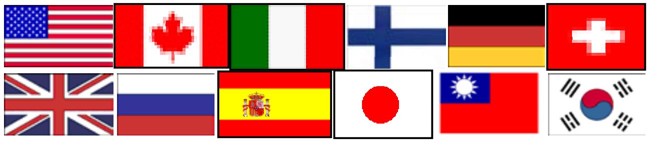
- **The program was laid out in a series of workshops between 1998 and 2000**
  - **http://fnth37.fnal.gov/run2.html**

- **The program stretches from the GeV scale to the TeV scale**

- **Here I can attempt only a superficial survey and will concentrate on the physics that gains most from luminosity**
  - **To see the full breadth of the program, I encourage you to visit the APS/DPFmeeting next week**
    - **~110 talks from CDF and DØ!**

Two Worldwide Collaborations

More than 50% non-US: a central part of the World Program

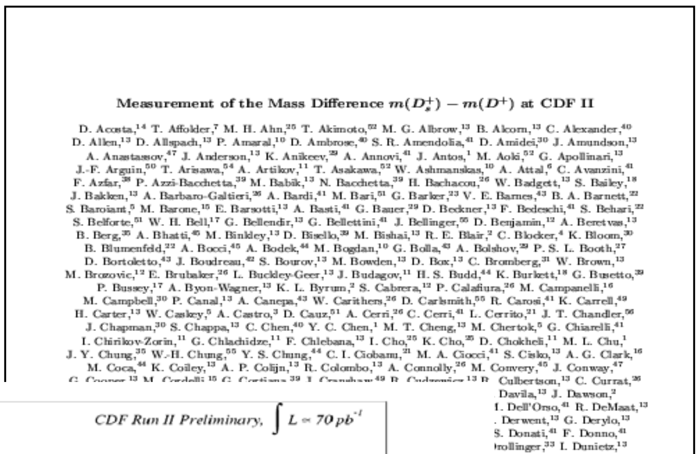


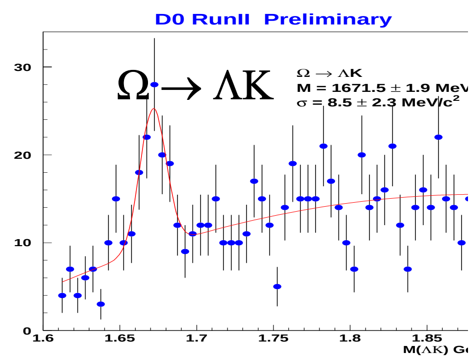
12 countries, 59 institutions
706 physicists

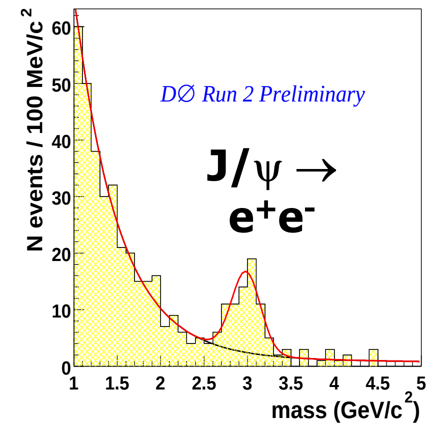
18 countries, 78 institutions
650 physicists

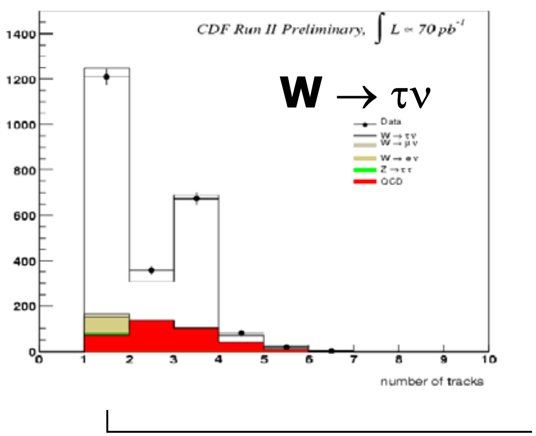
Operations Status

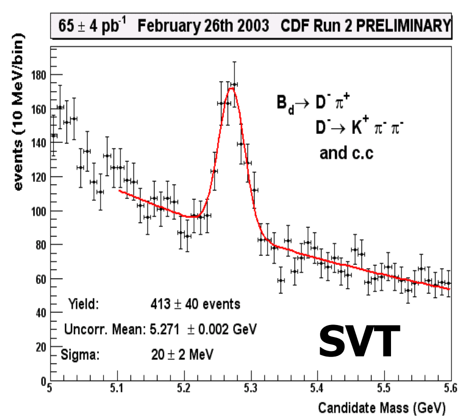
- Both experiments are operating well and recording physics quality data with high (85-90%) efficiency and record luminosities
- 50-90 pb^{-1} being used for analysis
- Data are being reconstructed within a few days

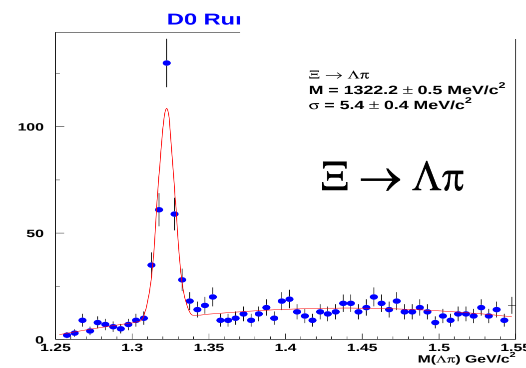

Measurement of the Mass Difference $m(D_s^+) - m(D^+)$ at CDF II





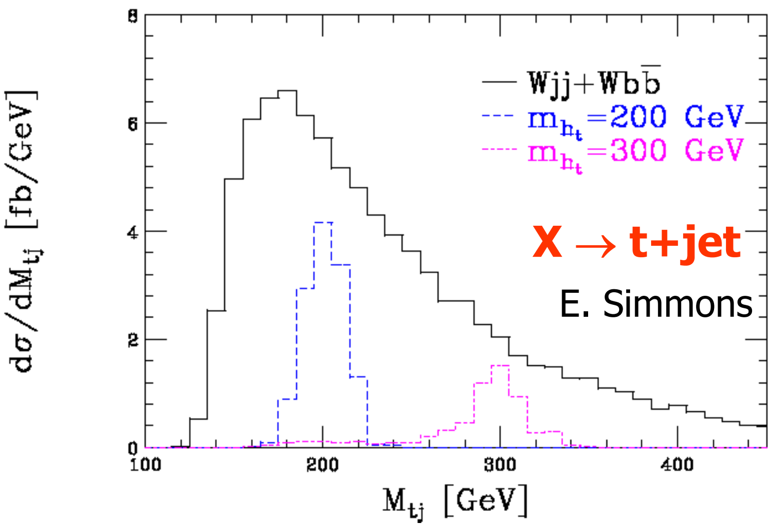




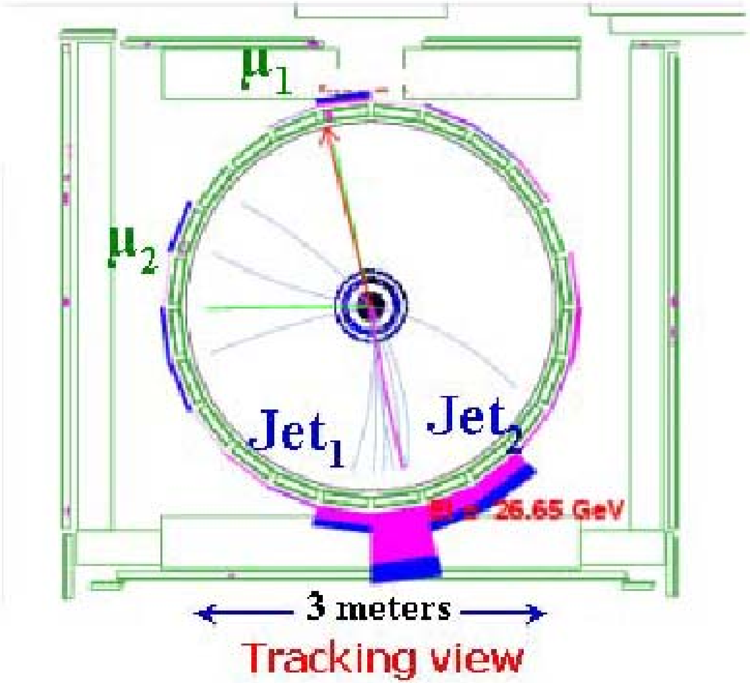


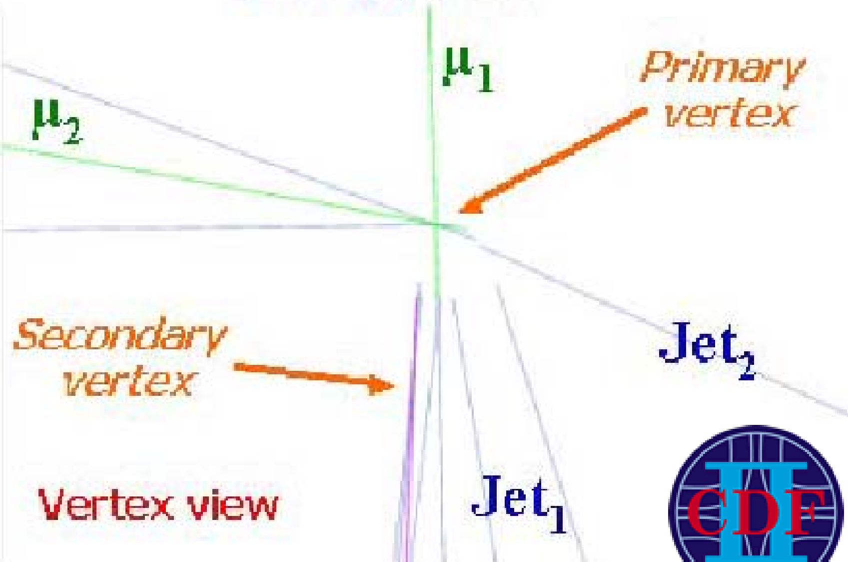
The Top Quark

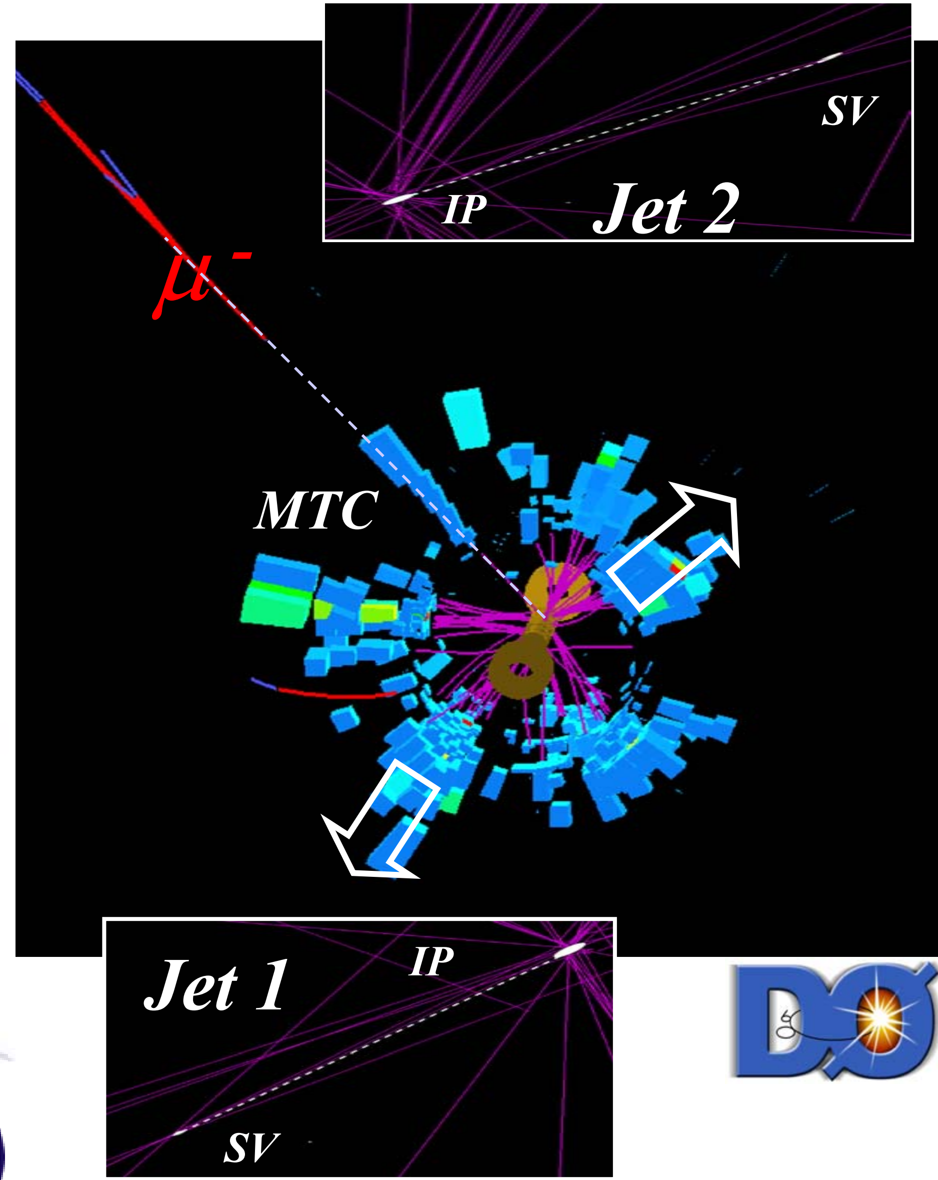
- Why, alone among the elementary fermions, does the top quark couple strongly to the Higgs field?
  - Is nature giving us a hint here?
    - Is the mechanism of fermion mass generation indeed the same as that of EW symmetry breaking?
  - The top is a window to the origin of fermion masses
- The Tevatron Collider is the world's only source of top quarks
- We will measure its
  - Mass
  - Production cross section
  - Spin
    - Through top-antitop spin correlations
  - Electroweak properties
    - Through single top production



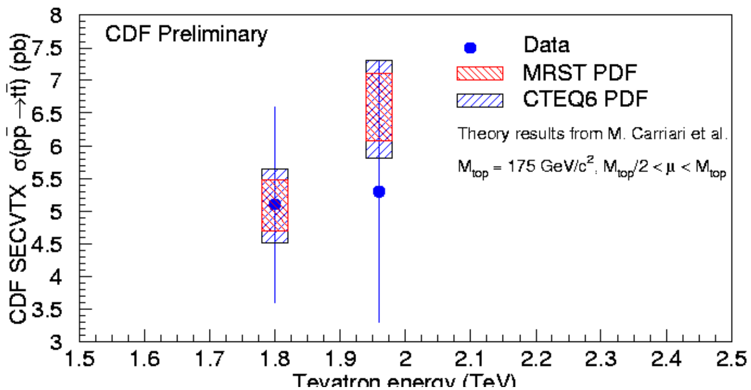
The Run II Top Physics Program has begun


μ_1
μ_2
Jet_1
Jet_2
26.65 GeV
3 meters
Tracking view


μ_1
μ_2
Primary vertex
Secondary vertex
Jet_2
Jet_1
Vertex view

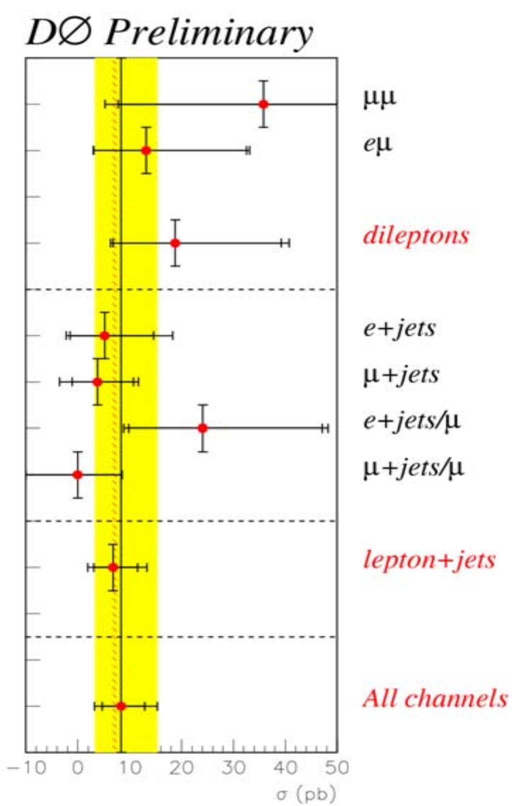

μ^-
SV
IP
Jet 2
MTC
Jet 1
IP
SV

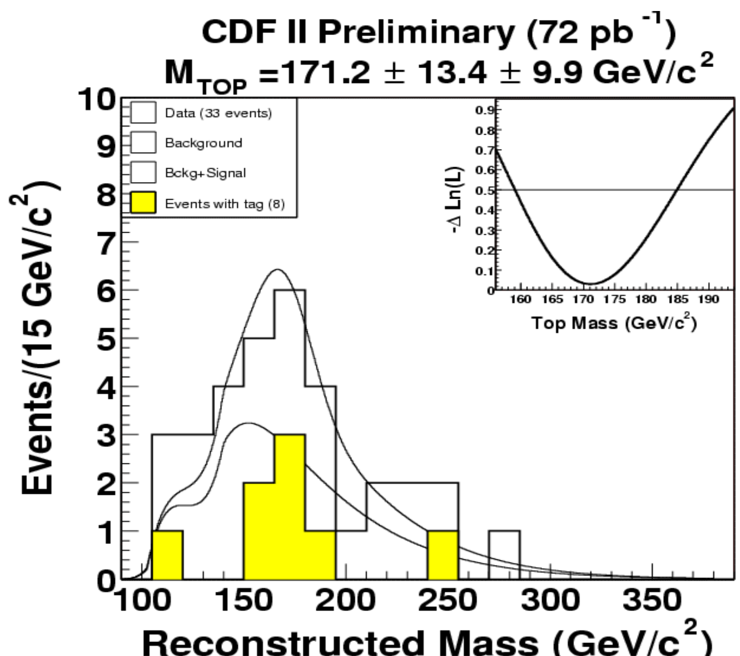
The top quark rediscovered, 2003



Cross section

$$CDF\ dileptons\ \sigma = 13.2 \pm 5.9_{stat} \pm 1.5_{sys}\ pb$$
$$CDF\ l + jets\ \sigma = 5.3 \pm 1.9_{stat} \pm 0.8_{sys} \pm 0.8_{lum}\ pb$$
$$D\O\ \ \sigma = 8.4^{+4.5}_{-3.7}(stat)\,^{+5.3}_{-3.5}(syst) \pm 0.8(lumi) pb$$



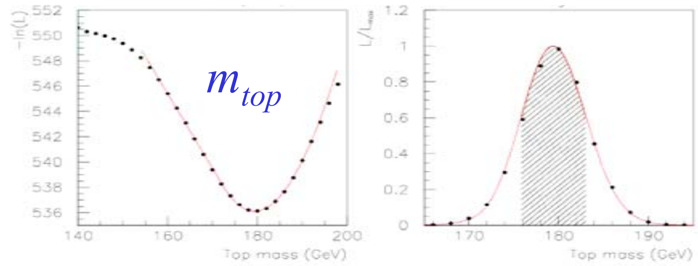


CDF mass

$$M_{top} = 171.2^{+14.4}_{-12.5\ stat} \pm 9.9_{sys}\ GeV/c^2$$

Top mass

- We can look forward to improved precision on m_t in the near future
  - More data (few hundred pb^{-1})
  - Expect ~ 500 b-tagged lepton+jets events per experiment per fb^{-1}
    - cf. World total at end of Run I ~ 100
- Improved techniques
  - e.g. new DØ Run I mass measurement is equivalent to a factor 2.4 in statistics:



$$m_{top} = 179.9 \pm 3.6 \quad (stat)\ GeV/c^2$$ *(5.6 GeV from PRD 58 052001,1998)*

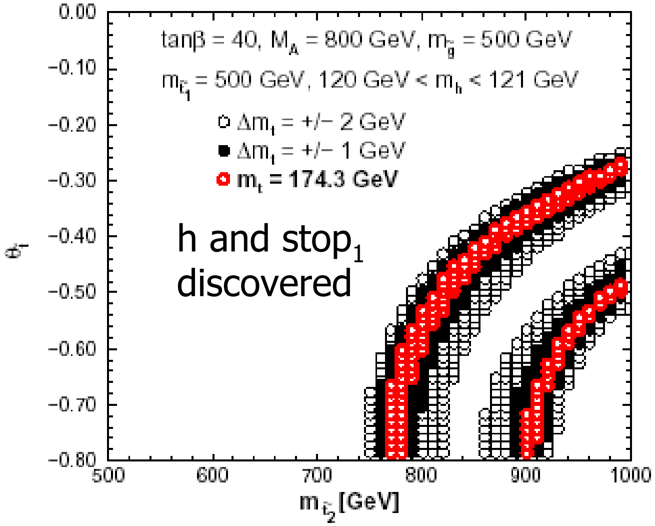
- Improved top mass measurements help to constrain the Higgs mass

	Δm_t
2 fb^{-1}	± 2.7 GeV
15 fb^{-1}	± 1.3 GeV

(using the "classic" technique)

Top physics program

- **Precise knowledge of m_t (~1 GeV) will be very useful even after a light Higgs is discovered**
  - **Is it H_{SM} or SUSY h?**
  - **Constrain the stop sector:**
    [M. Beneke et al., hep-ph/0003033]



- **Single top production**
  - **So far unobserved**
  - **With ~ 1 fb^{-1} should be able to see signals for both s and t-channel production (have different sensitivity to new physics)**

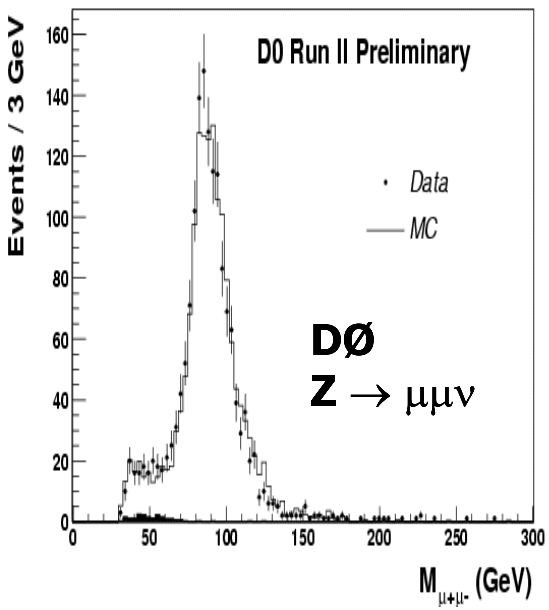
	$\Delta\sigma$ (s)	$\Delta\lvert V_{tb}\rvert$(s)	$\Delta\sigma$ (t)	$\Delta\lvert V_{tb}\rvert$(t)
2 fb^{-1}	21%	12%	12%	10%
10 fb^{-1}	9%	6%	5%	8%

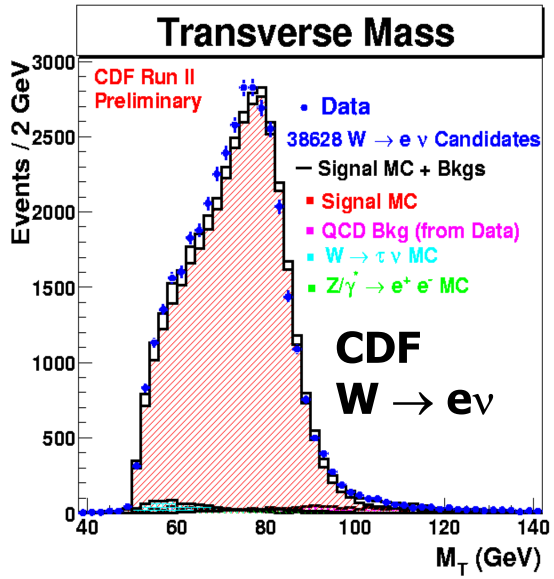
[scaled from T. Stelzer, Z. Sullivan and S. Willenbrock, Phys. Rev. ***D58****, 094021 (1998)]*

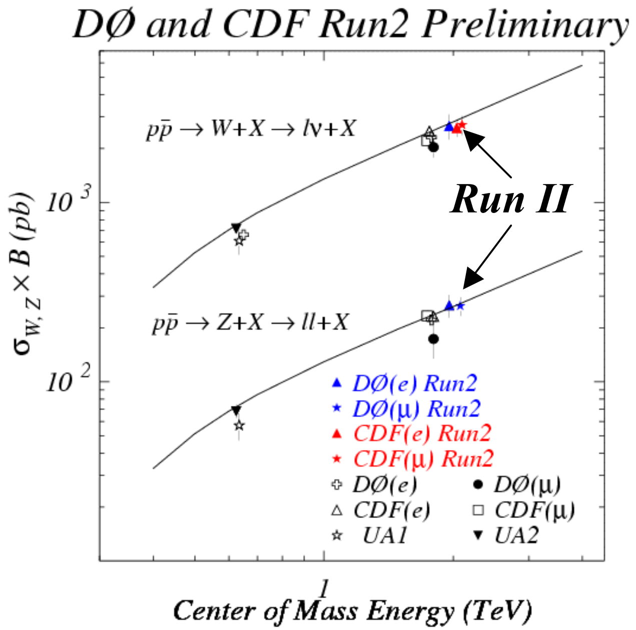
- **Top spin correlations**
  - **With 2fb^{-1}, can distinguish spin-½ from spin-0 only at the 2σ level**

Electroweak Physics

- **In Run II we will complement direct searches for new phenomena with indirect probes**
  - **New particles and forces can be seen indirectly through their effects on electroweak observables.**
  - **Tightest constraints come from improved determination of the masses of the W and the top quark.**
- **Both experiments have preliminary results from Run II samples of W and Z candidates:**



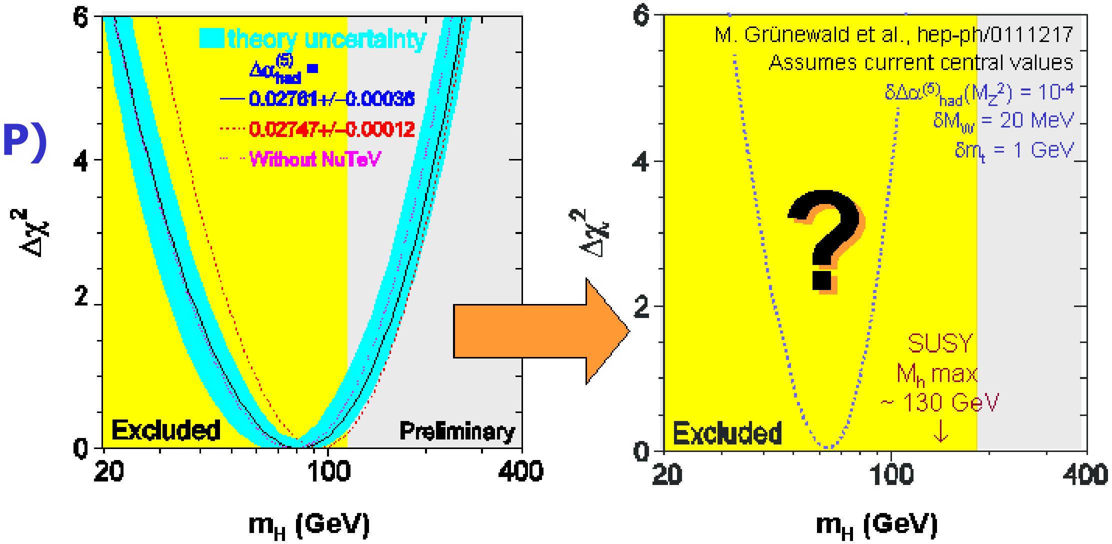




Prospects for W mass

Current knowledge of m_W

- **DØ:**
  - **80 483 ± 84 MeV**
- **hadron colliders:**
  - **80 454 ± 59 MeV**
- **World (dominated by LEP)**
  - **80 451 ± 33 MeV**



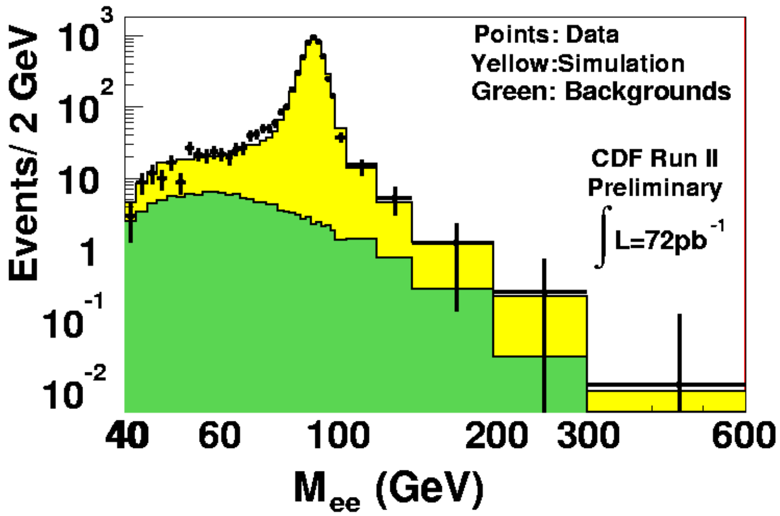
Run II prospects
(per experiment)

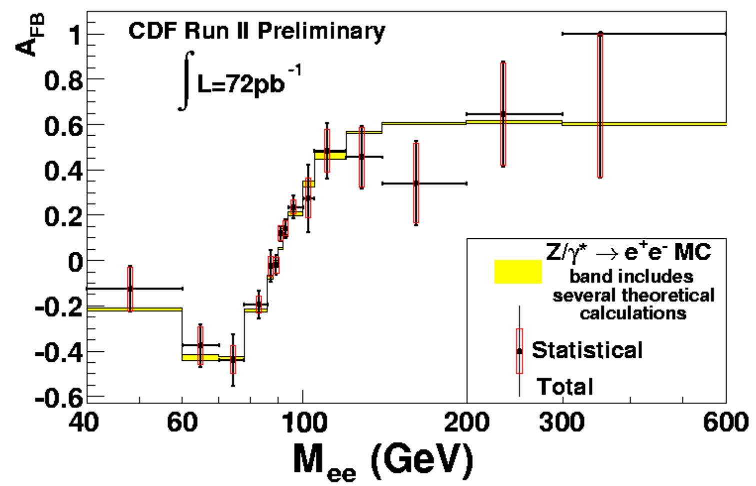
	Δm_W
2 fb^{-1}	**±27 MeV**
15 fb^{-1}	**±15 MeV**

We have shown we can measure the W mass precisely at the Tevatron, but to improve on LEP will require ~ fb^{-1} datasets - not a short term goal

Other electroweak measurements

- Forward-backward asymmetry in $Z \rightarrow ee$





CDF
Paper in preparation

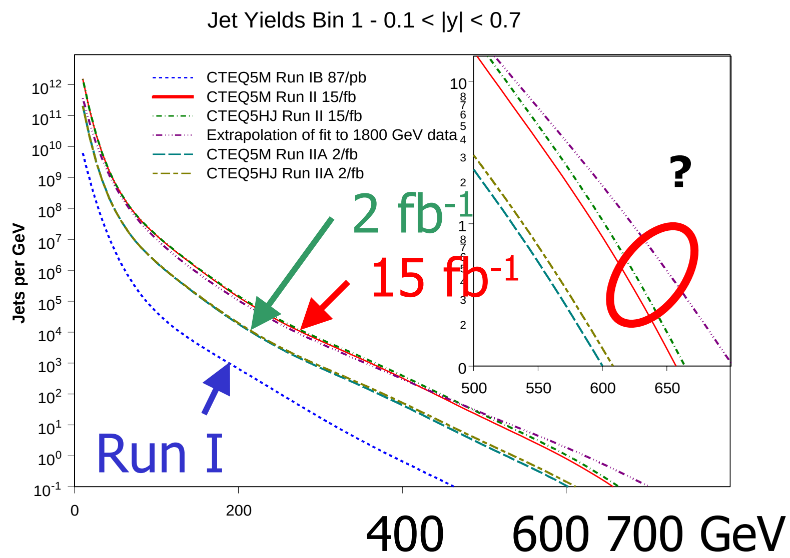
- Multiboson production, boson plus jets…

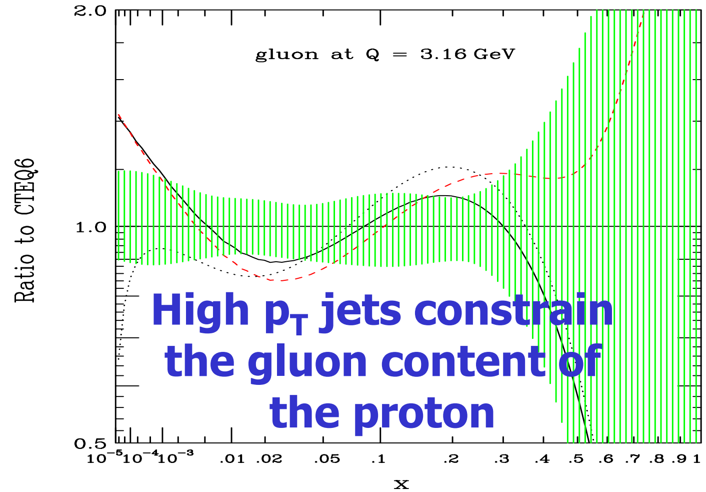
QCD

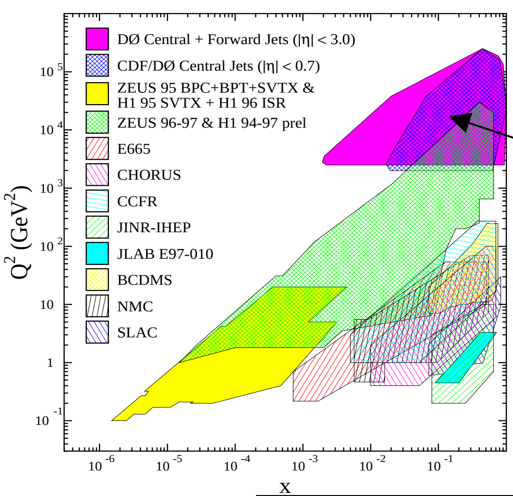
- No one doubts that QCD describes the strong interaction between quarks and gluons
  - Its effects are all around us:
    - masses of hadrons (stars and planets)
  - But it is not an easy theory to work with

- Use the Tevatron to
  - Test QCD itself
  - Understand some outstanding puzzles from Run I
  - Develop the expertise to calculate, and confidence in, the backgrounds to new physics

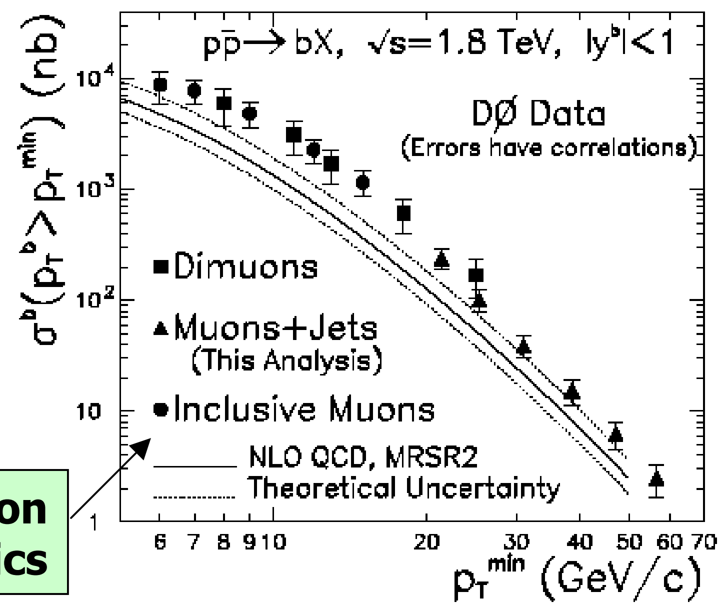
Some QCD Physics goals for Run II







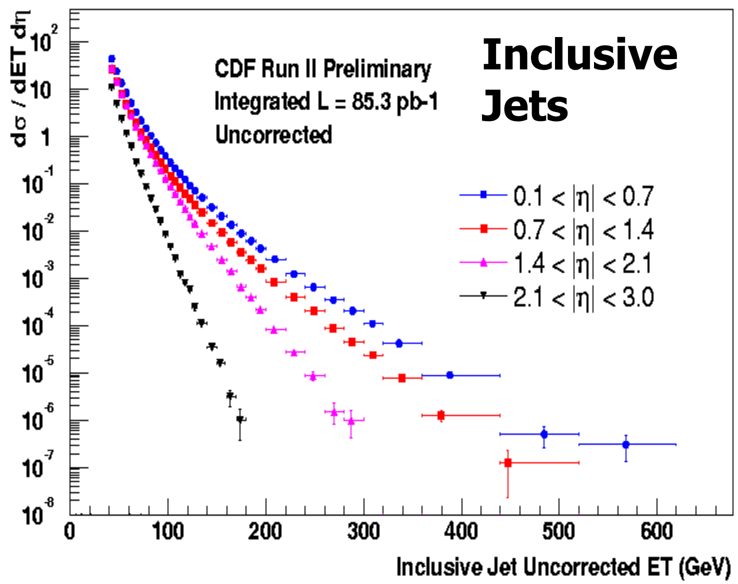
Run I jet data already used in CTEQ6 and MRST2001 parton distribution fits Complement HERA's kinematic range

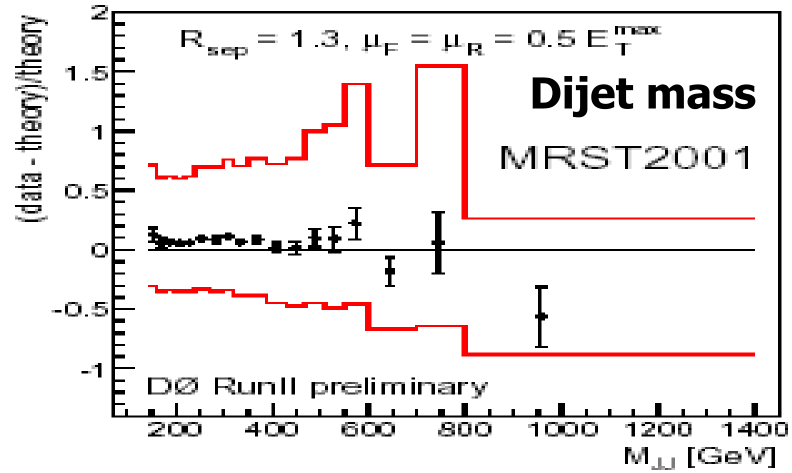


b-jet cross section
Important background to new physics

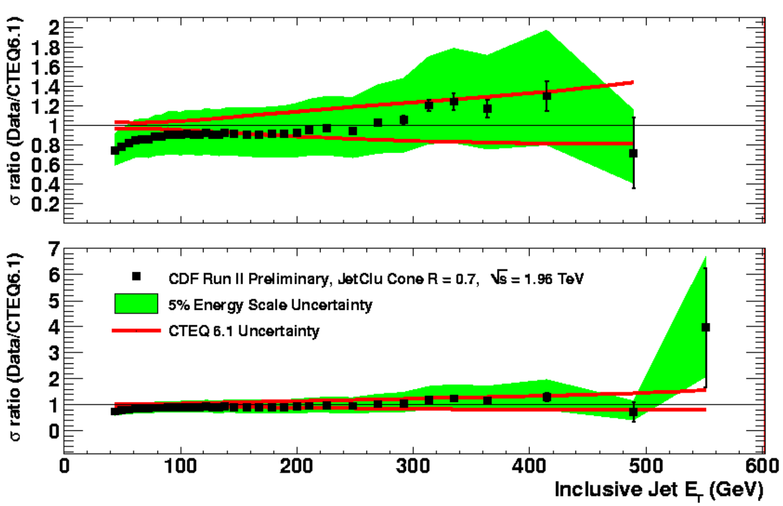
John Womersley

Jets in Run II

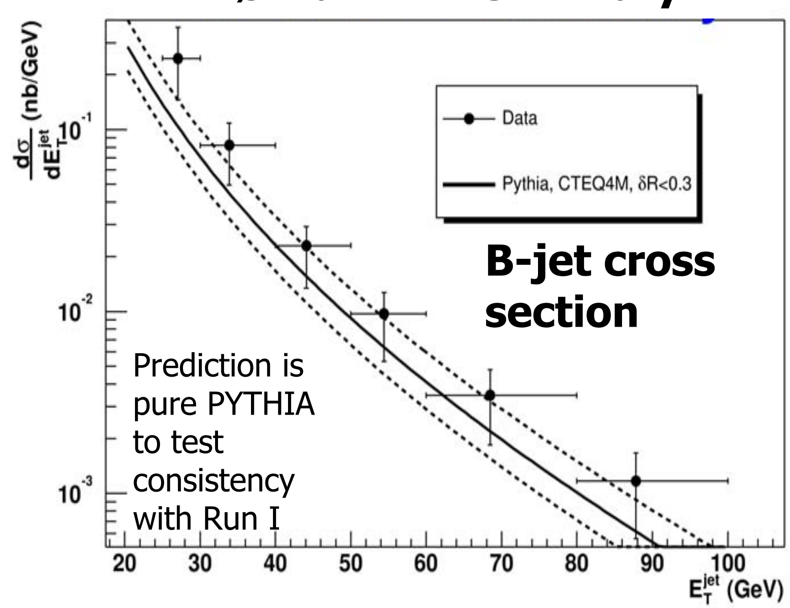




CDF Run II Preliminary



DØ Run II Preliminary



Searches for New Physics

- The Tevatron, as the world's highest energy collider, is the most likely place to directly discover a new particle or force
- We know the SM is incomplete
  - Most popular extension: supersymmetry
- Predicts multiple Higgs bosons, strongly interacting squarks and gluinos, and electroweakly interacting sleptons, charginos and neutralinos
  - masses depend on unknown parameters, expected to be 100 GeV - 1 TeV

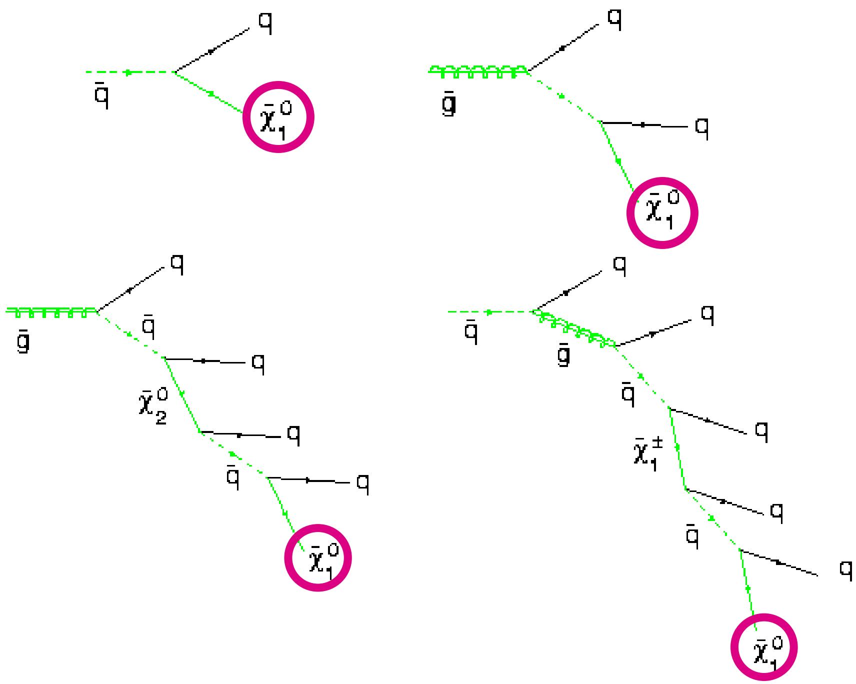
Lightest neutralino is a good candidate for cosmic dark matter
Potentially discoverable at the Tevatron

Supersymmetry signatures

- **Squarks and gluinos are the most copiously produced SUSY particles**
- **As long as R-parity is conserved, cannot decay to normal particles**
  - **Jets plus missing transverse energy signatures**

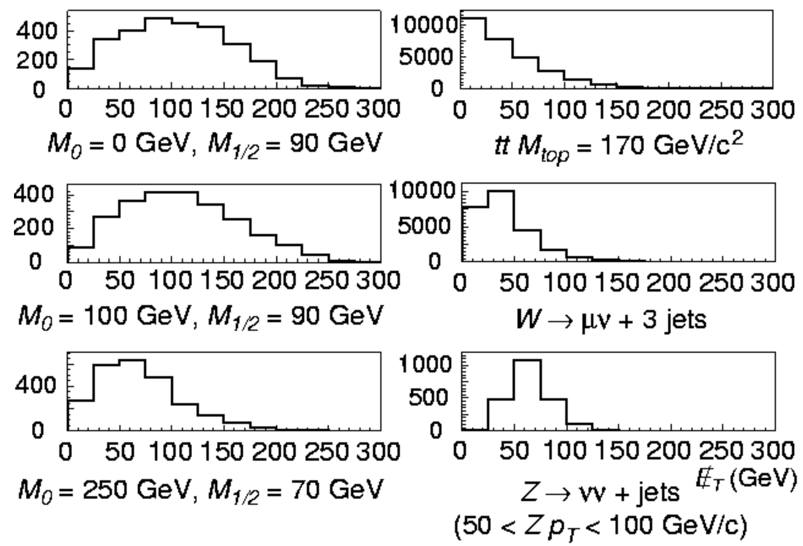
Make dark matter at the Tevatron! → **Detect its escape from the detector**

Possible decay chains always end in the LSP



Missing E_T

SUSY **backgrounds**



Search region typically > 75 GeV

John Womersley

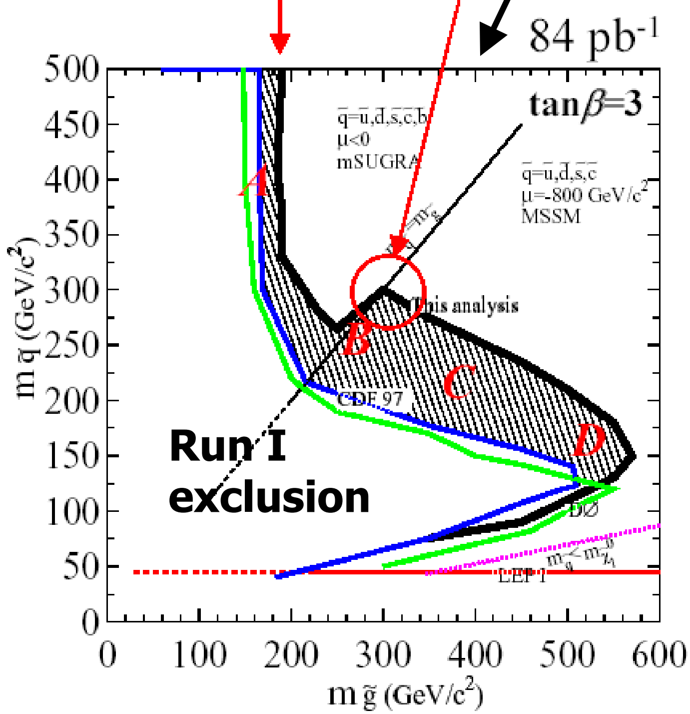
Searching for squarks and gluinos

Run I

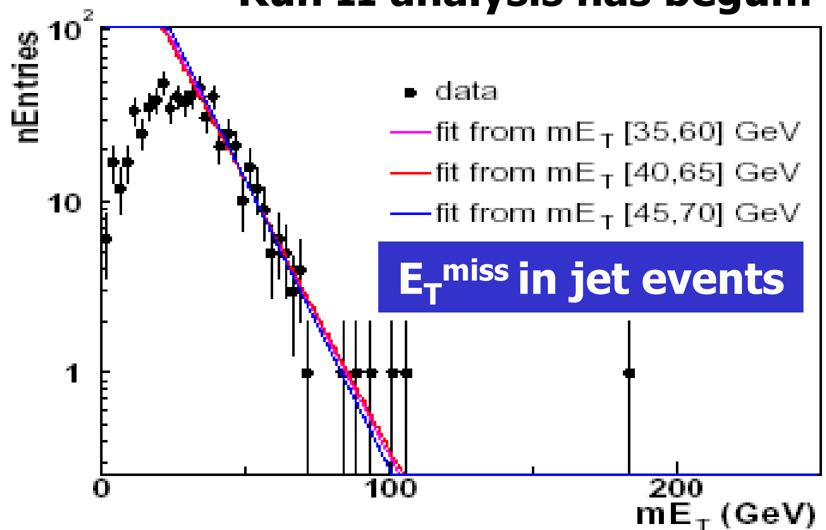
$M_{\tilde{g}} > 300\ \mathrm{GeV/c^2} \quad M_{\tilde{q}} \approx M_{\tilde{g}}$

$M_{\tilde{g}} > 195\ \mathrm{GeV/c^2}$

Reach with 2 fb^{-1}: gluino mass ~ 400 GeV

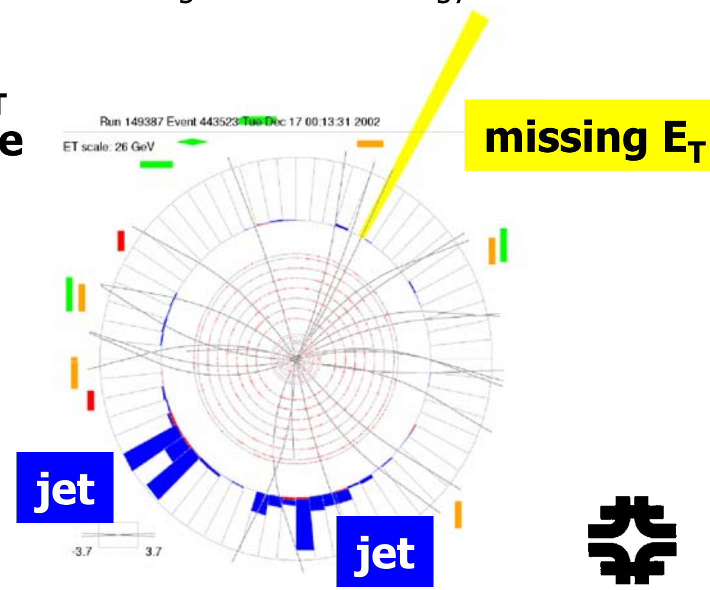


Run II analysis has begun:



Missing Transverse Energy

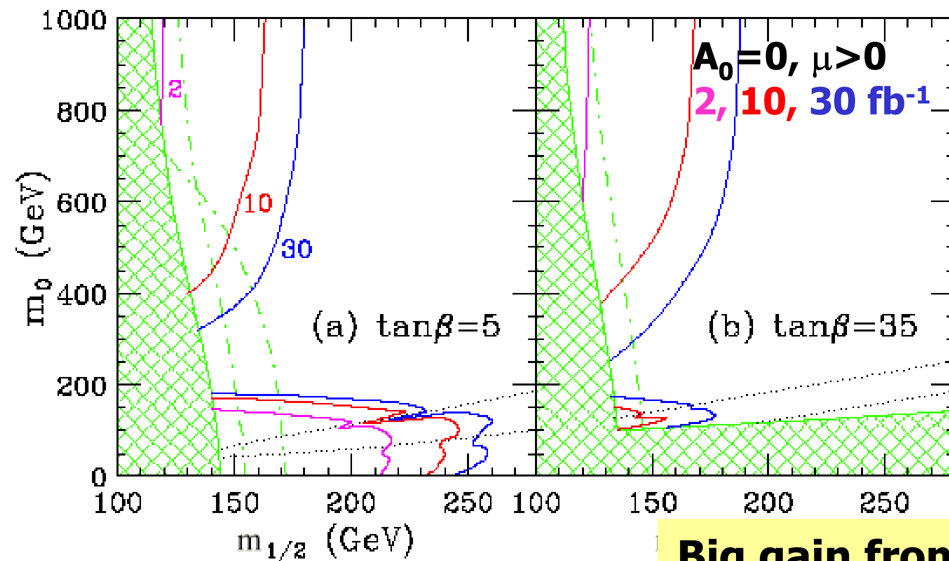
High ME$_T$ candidate event



John Womersley

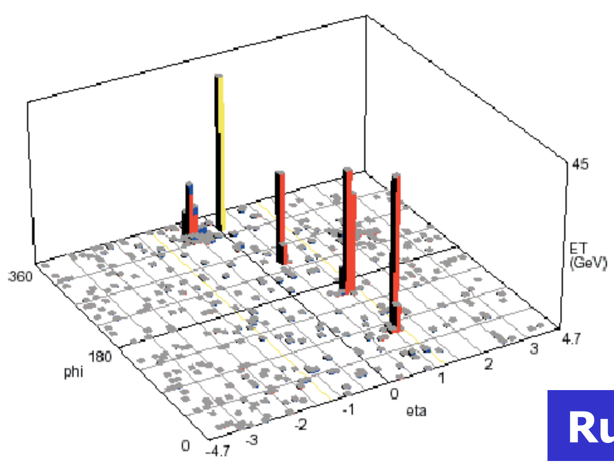
Chargino/neutralino production

- "Golden" signature
  - Three leptons
    - very low standard model backgrounds
- This channel becomes increasingly important as squark/gluino production reaches its kinematic limits (masses ~ 500 GeV)



Big gain from 2 to 10 fb^{-1}

- Reach on $\chi^{\pm}$ mass, 2fb^{-1} ~ 180 GeV ($\tan\beta = 2$, $\mu< 0$)
  ~ 150 GeV (large $\tan\beta$)

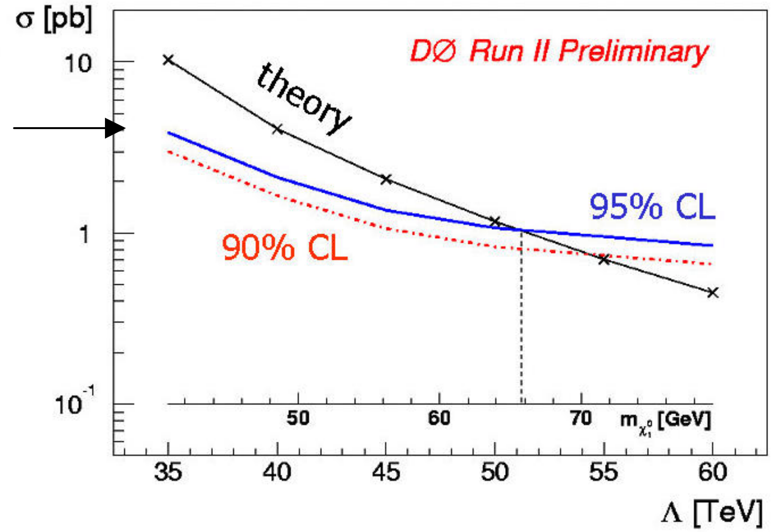


Searches have begun.
So far number of events is consistent with expectations — we need a lot more data, but the tools are in place

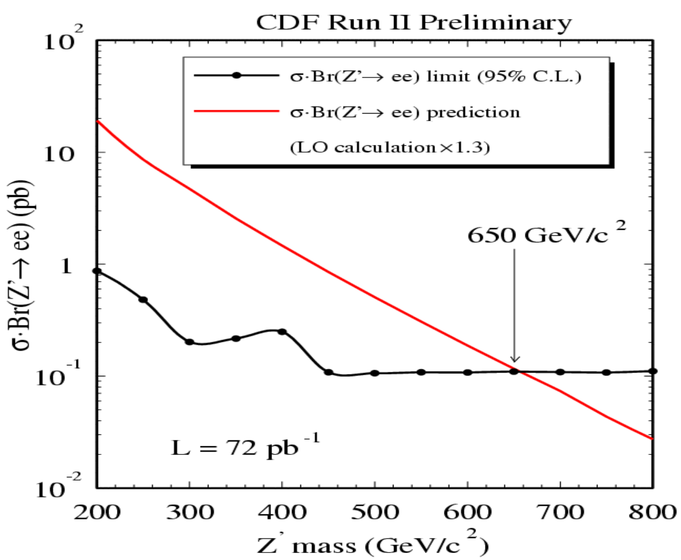
Run II Trilepton candidate

Other Searches at the Tevatron

- **Other Tevatron search channels for SUSY**
  - GMSB → Missing E_T + photon(s)
  - Stop, sbottom
  - RPV signatures
- **Searches for other new phenomena**
  - leptoquarks, dijet resonances, W’,Z’, massive stable particles, doubly charged particles…



Close to Run I limits!

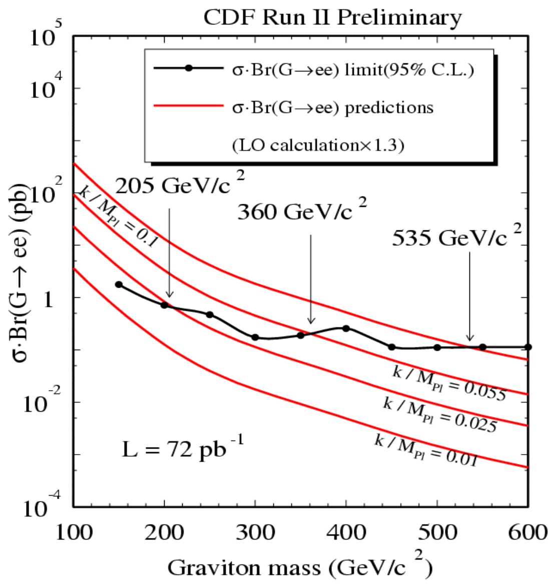


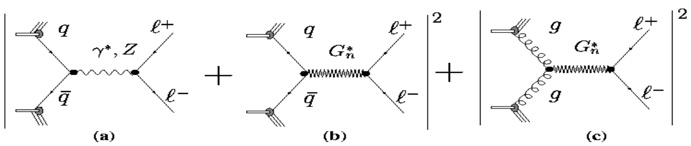
CDF Run II Z’ > 650 GeV/c²

Cf. Run I:
640/670 GeV/c² (CDF/D0)

Extra Dimensions

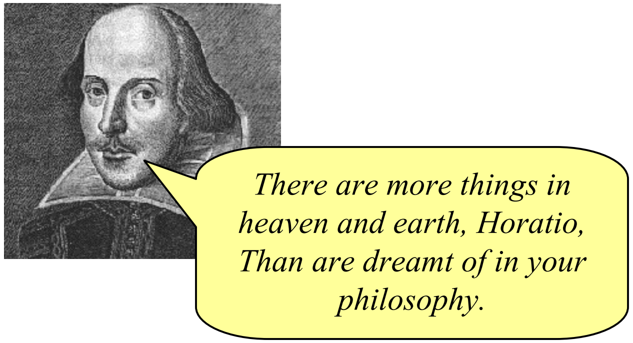
- Run II is also testing the new and exciting idea of extra dimensions
  - Can gravity propagate in more than four dimensions of space-time?
  - If these dimensions are not open to the other SM particles and forces, we would not perceive them
  - Particle physics experiments at the TeV scale could see effects (direct and indirect)
    - Measure the structure of space-time!





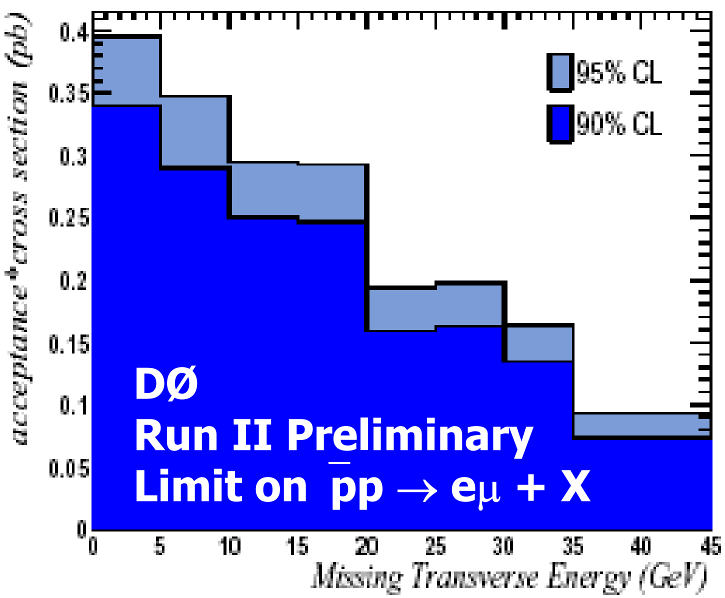
	GRW	HLZ for n: 2	7	Hewett $\lambda = +1$
diEM	1.12	1.16	0.89	1.00
diMU	0.79	0.68	0.63	0.71

With 300 pb^{-1}, we probe up to 1.6 TeV
With 2 fb^{-1}, we probe up to 2 TeV

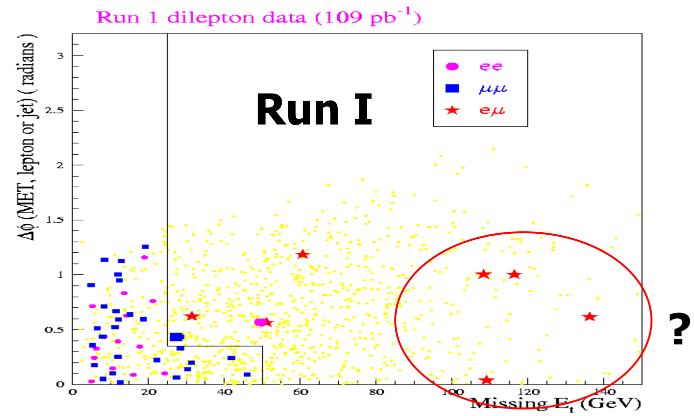


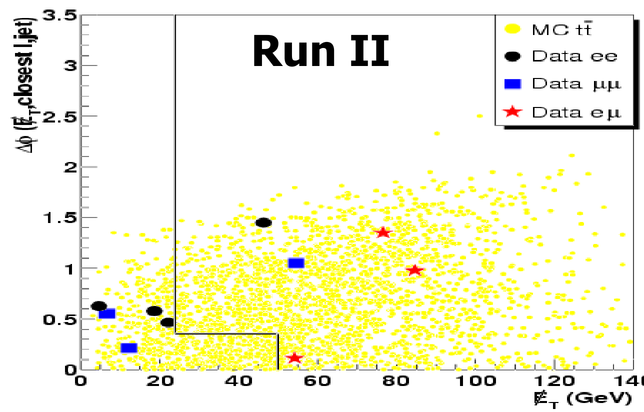
Signature-based searches

We need to ensure that our searches are not constrained by our preconceptions of what might be "out there."



CDF dilepton top events





Follow up anomalies in Run I data, and set model-independent limits

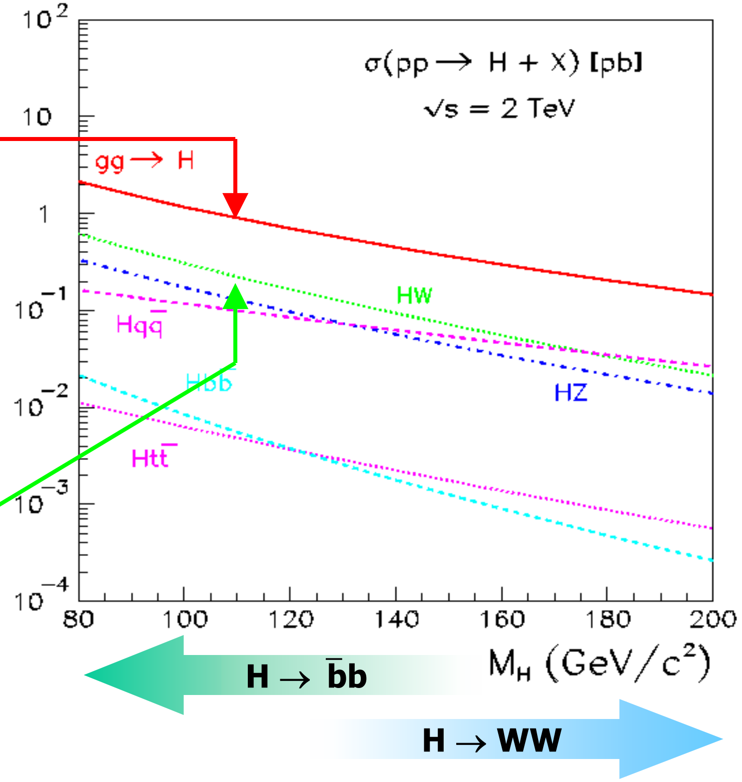
"Sleuth" framework used very successfully by DØ in Run I

The Higgs Boson

- In the Standard model, the weak force is weak because the W and Z gain mass from a scalar field that fills the universe
- The same field is responsible for the mass of the fundamental fermions
- If it exists, we can excite the field and observe its quanta in the lab
  - The Higgs boson
    - Last piece of the SM
    - Key to understanding beyond-the-SM physics like supersymmetry: a light Higgs is a basic prediction of SUSY
- All the properties of the Higgs are fixed in the SM with the exception of its own mass: simulations have no free parameters

Higgs Hunting at the Tevatron

- For any given Higgs mass, the production cross section and decays are all calculable within the Standard Model
- Inclusive Higgs cross section is quite high: ~ 1pb
  - for masses below ~ 140 GeV, the dominant decay is H → bb which is swamped by background
  - at higher masses, can use inclusive production plus WW decays
- The best bet below ~ 140 GeV appears to be associated production of H plus a W or Z
  - leptonic decays of W/Z help give the needed background rejection
  - cross section ~ 0.2 pb

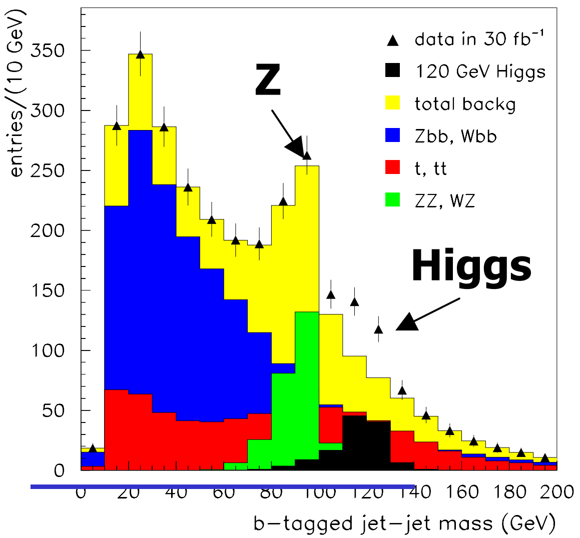


Dominant decay mode

$m_H \lesssim 140$ GeV: $H \to b\bar{b}$

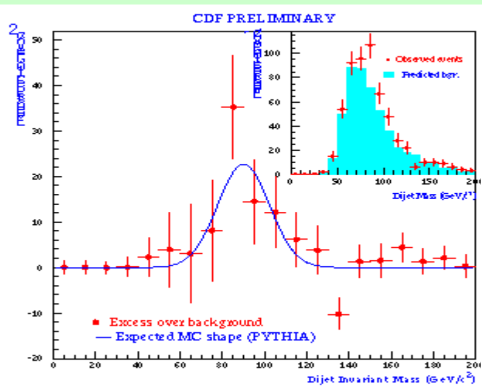
- $WH \to q\bar{q}' b\bar{b}$ is the dominant decay mode but is overwhelmed by QCD background
- $WH \to l^{\pm}\nu\, b\bar{b}$ backgrounds $W b\bar{b}$, WZ, $t\bar{t}$, single top
- $ZH \to l^{+}l^{-}\, b\bar{b}$ backgrounds $Z b\bar{b}$, ZZ, $t\bar{t}$
- $ZH \to \nu\nu\, b\bar{b}$ backgrounds QCD, $Z b\bar{b}$, ZZ, $t\bar{t}$
  - powerful but requires relatively soft missing E_T trigger (~ 35 GeV)

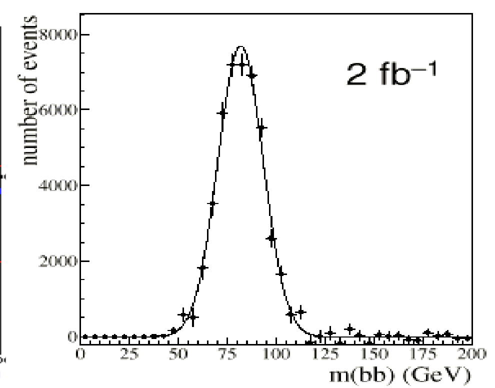
m_H = 120 GeV



2 × 15fb⁻¹ (2 experiments)

$b\bar{b}$ mass resolution
Directly influences signal significance
$Z \to b\bar{b}$ will be a calibration





CDF $Z \to b\bar{b}$ in Run I **DØ simulation for 2fb⁻¹**

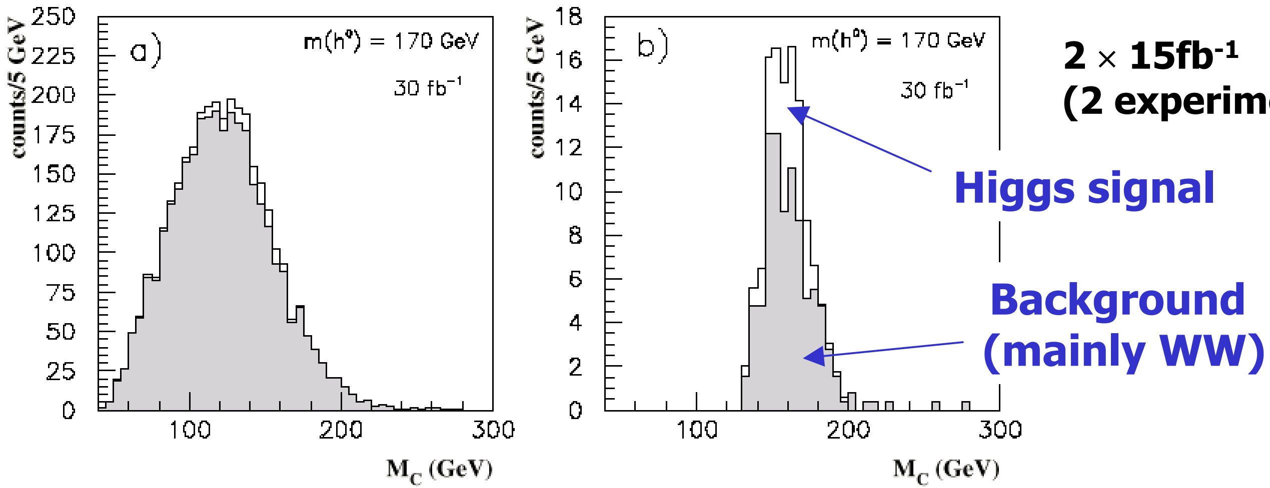
John Womersley

$m_H \gtrsim 140$ GeV : $H \rightarrow WW^{(*)}$

- **$gg \rightarrow H \rightarrow WW^{(*)} \rightarrow l^+l^- \nu\nu$**

Backgrounds **Drell-Yan, WW, WZ, ZZ, tt, tW, $\tau\tau$**
Initial signal:background ratio ~ 10^{-2}

- **Angular cuts to separate signal from "irreducible" WW background**



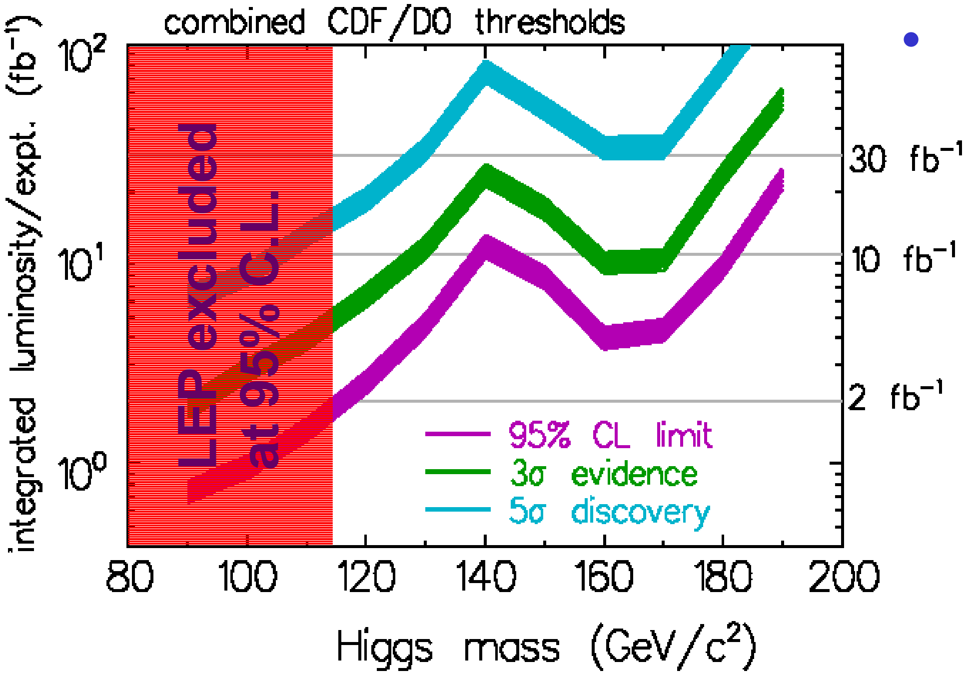
2 × 15fb^{-1}
(2 experiments)

Before tight cuts: verify WW modelling

After tight cuts

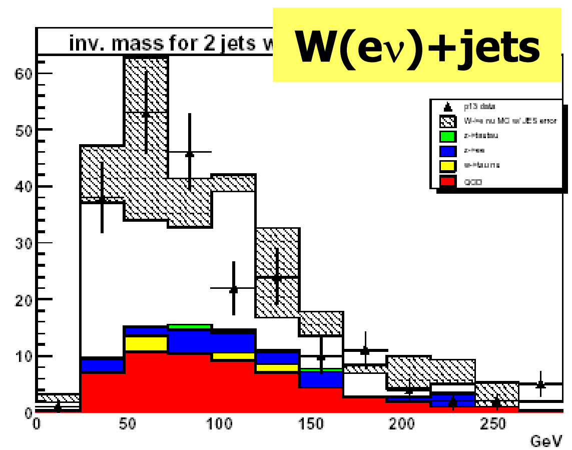
$$M_C = \textit{cluster transverse mass} \quad = \sqrt{p_T^2(\ell\ell) + m^2(\ell\ell)} + \not{E}_T$$

The famous Higgs Reach plot



- **To make this a reality, we need**
  - **Two detectors**
  - **Good Resolutions**
  - **Good b-jet and lepton identification**
  - **Triggers efficient at high luminosities**
  - **Good understanding of all the backgrounds:**

CDF and DØ have a joint effort underway to re-evaluate some key channels in this Higgs reach plot. Results by ~ June.

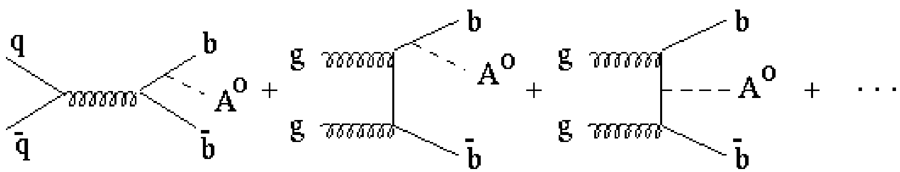


Di-jet Mass

John Womersley

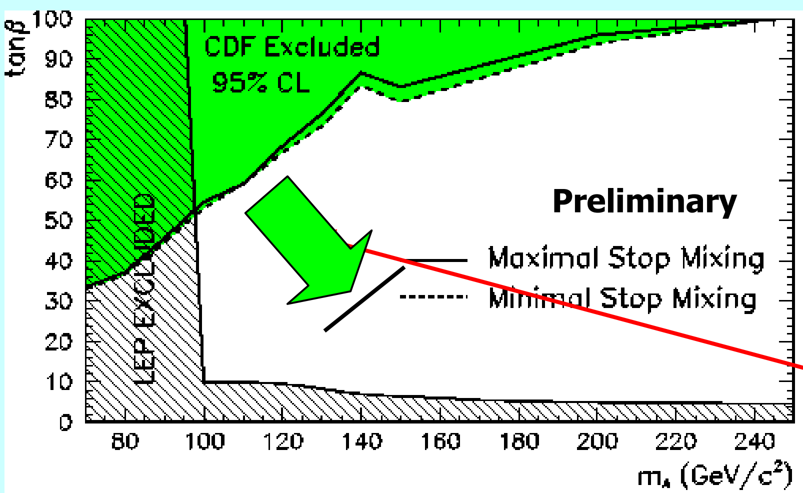
SUSY Higgs Production at the Tevatron

- bb(h/H/A) enhanced at large tan β:

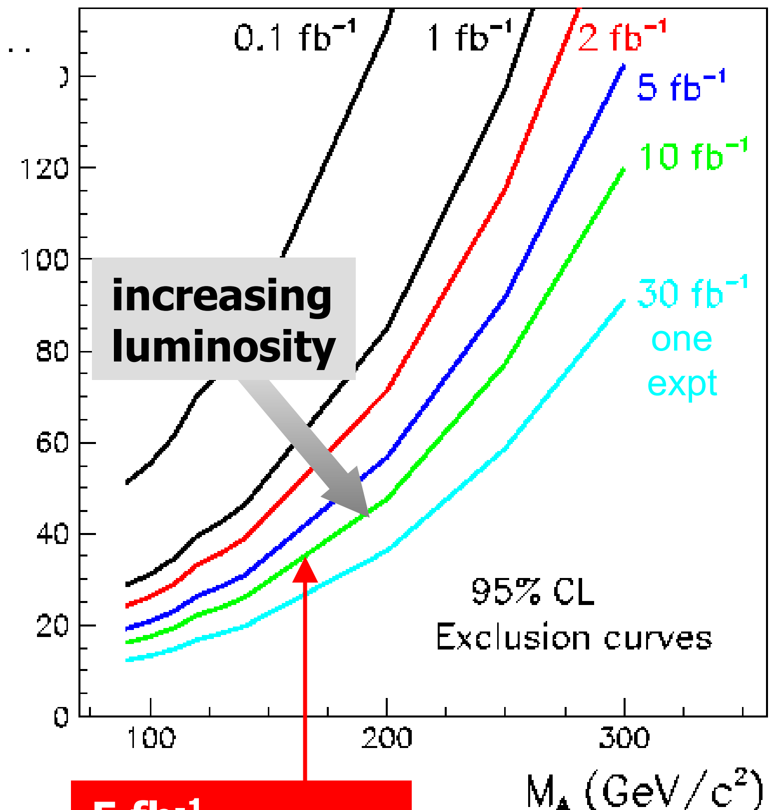


- σ ~ 1 pb for tanβ = 30 and m_h = 130 GeV

CDF Run I analysis (4 jets, 3 b tags) sensitive to tan β > 60



bb(h/A) → 4b



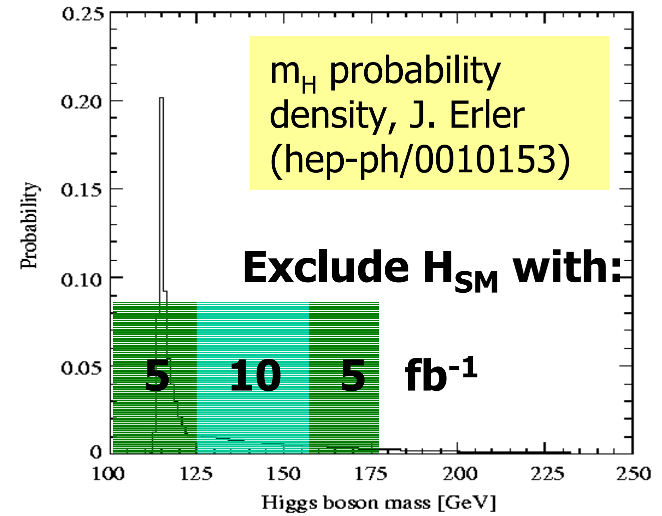
5 fb^{-1}
m_A =140 GeV,
tan β = 30

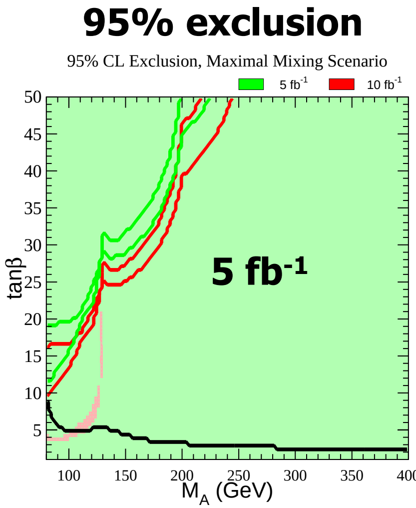
John Womersley

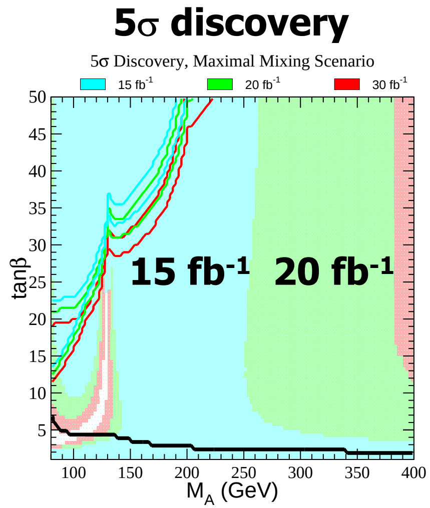
What if we see nothing?

As long as we have adequate sensitivity, exclusion of a Higgs would itself be a very important discovery for the Tevatron

- In the SM, can exclude most of the allowed mass range with 10 fb^{-1}
- In the MSSM, can potentially exclude
  <u>all</u> the remaining parameter space with 5 - 10 fb^{-1}
- Would certainly make life "interesting" for SUSY at the TeV scale







Exclusion and discovery for SUSY Higgs sector, maximal stop mixing, sparticle masses = 1 TeV

Run II Physics Program

15 fb^{-1}
- 5σ Higgs signal @ m_H = 115 GeV
- 3σ Higgs signal @ m_H = 115-135, 150-175 GeV
- Reach ultimate precision for top, W, B physics

10 fb^{-1}
- 3σ Higgs signal @ m_H = 115-125, 155-170 GeV
- Exclude Higgs over whole range of 115-180 GeV
- Possible discovery of supersymmetry in a larger fraction of parameter space

5 fb^{-1}
- 3σ Higgs signal @ m_H = 115 GeV
- Exclude SM Higgs 115-130, 155-170 GeV
- Exclude much of SUSY Higgs parameter space
- Possible discovery of supersymmetry in a significant fraction of minimal SUSY parameter space (the source of cosmic dark matter?)

2 fb^{-1}
- Measure top mass ± 3 GeV and W mass ± 25 MeV
- Directly exclude m_H = 115 GeV
- Significant SUSY and SUSY Higgs searches
- Probe extra dimensions at the 2 TeV (10^{-19} m) scale
- B physics: constrain the CKM matrix

300 pb^{-1}
- Improved top mass measurement
- High p_T jets constrain proton structure
- Start to explore B_s mixing and B physics
- SUSY Higgs search @ large tan β
- Searches beyond Run I sensitivity

Each gain in luminosity yields a significant increase in reach and lays the foundation for the next steps

John Womersley

Complementarity

- The two detectors have different emphases
  - CDF detector emphasizes charged particle tracking
  - DØ detector emphasizes calorimetry, standalone muon system
- Use complementary technologies and approaches
- We believe they have comparable reach for the physics of interest in the later stages of Run II (top, W/Z, high-p_T jets, SUSY, Higgs)
  - Acceptances, lepton, jet and b-tagging capabilities are very similar
  - Search reach is usually dominated by production cross sections and physics backgrounds

Why upgrade two detectors?

- The 1997 HEPAP subpanel suggested upgrading only one detector. What has changed?
  - That recommendation was made in the context of a Run III with 10^{33} luminosity and $20 fb^{-1}$ delivered per detector before the LHC
  - Would have required more extensive (and expensive) upgrades
  - Subsequently it became clear that this accelerator performance was not reasonably achievable
- The Run II Physics Workshops (1998-2000) emphasized that the best way to maximize physics reach is to operate two detectors and combine their results
  - Achieves a doubling of the effective luminosity with very low technical risk
    - Maximizing luminosity is always critical at the energy frontier
    - This is the most cost-effective factor of two to be had
  - Also
    - Assures the spur of mutual competition and the ability to cross-check results
    - Gives a broader, stronger program
    - Provides insurance

Conclusions

- **The Run II physics program has begun**
- **The combination of highest accelerator energy, excellent detectors, enthusiastic collaborations, and data samples that double every year guarantees interesting new physics results at every step.**
- **Each step answers important questions, and each step leads on to the next**
- **The goal of the Run IIb detector upgrades is to**
  - **maximize this physics program**
  - **exploit the full potential of the world's highest energy collider and the large investments we have made in the accelerator and detectors**
  - **Lay a firm foundation for the LHC and for future initiatives at the TeV scale**